

Estimation of charm production cross section in hadronic interactions at high energies

G.M. Vereshkov^{1,2*}; Yu.F. Novoseltsev^{2†}

¹Physics Research Institute of Rostov State University,

²Institute for Nuclear Research of RAS

Abstract

Results of processing experimental data on charm production in hadron-hadron interactions are presented. The analysis is carried out within the frame of phenomenological model of diffraction production and quark statistics based on additive quark model (AQM). In low energy region $\sqrt{s} = 20 - 40$ GeV, the cross sections $\sigma_{pN \rightarrow c\bar{c}X}(s)$, $\sigma_{\pi N \rightarrow c\bar{c}X}(s)$ are fitted by logarithmic function with the parameters connected by relationship of AQM. At collider energies 200, 540, 900, 1800 GeV, the values of $\sigma_{p\bar{p} \rightarrow c\bar{c}X}(s)$ were obtained by a quark statistics method from the data on diffraction dissociation. It is established, that logarithmic function with universal numerical parameters describes the whole set of low-energy and high-energy data with high accuracy. The expected values of cross sections are $\sigma_{pp \rightarrow c\bar{c}X} = 250 \pm 40 \mu b$ and $355 \pm 57 \mu b$ at TEVATRON energy $\sqrt{s} = 1.96$ TeV and LHC energy $\sqrt{s} = 14$ TeV accordingly. Opportunities of use of the obtained results for calibration of a flux of "prompt" muons in high-energy component of cosmic rays are discussed.

1 Introduction

The investigation of charm production processes at overaccelerator energies is an actual problem of elementary particles and cosmic rays physics. Nowadays there are four groups of experimental data:

- 1) data on total cross sections of charm production in hadron-hadron interactions $\sigma_{tot}(pN \rightarrow c\bar{c} + X)$, $\sigma_{tot}(\pi N \rightarrow c\bar{c} + X)$ in the region of low energies $\sqrt{s} = 20 - 40$ GeV;
- 2) data on total cross sections of charm production in a photon - hadron interactions $\sigma_{tot}(\gamma N \rightarrow c\bar{c} + X)$ at low energies $\sqrt{s} = 6 - 20$ GeV and - at virtualities of a photon up to $Q^2 = 4$ GeV² - in the region of high energies $\sqrt{s} = 160 - 240$ GeV;
- 3) data on production of J/Ψ , $\Psi(2S)$ particles in $p\bar{p}$ -interactions at $\sqrt{s} = 1800$ GeV [1], [2].
- 4) data on differential cross section of charm production in $p\bar{p}$ - interaction in the central area at $\sqrt{s} = 1960$ GeV and transverse momentum $p_T > 5.5$ GeV [3].

The first two groups of the data and the appropriate review of the literature contain, for example, in Ref. [4]. Only the first group of the data has the status of a direct information on charm production in hadron-hadron interactions. Three other groups differ from the first one by initial or final states, therefore the joint model independent processing of all three groups of the data is impossible. Accordingly, comparison of the theory to

*email: gveresh@ip.rsu.ru

†email: YuNovoselt@yandex.ru

experiment is at a loss also: fixing of parameters of theoretical model by its comparison to the one group of high-energy data results in catastrophic disagreements of the same model with other group of the data. In the scientific literature this situation is characterized as "an unsolved problem" [5].

In the present work an estimation of the total charm production cross section is offered. The estimation is based on processing of collider data on diffraction dissociation with use of phenomenological model of diffraction charm production and quark statistics. The result reduces to simple formula with well enough certain numerical parameters:

$$\sigma_{p\bar{p}/pp \rightarrow c\bar{c}+X}(s) = C_{p\bar{p}/pp} \ln \frac{s}{s_0}, \quad (1)$$

$$C_{p\bar{p}/pp} = 26.78 \pm 1.44 \mu b, \quad \sqrt{s_0} = 18.23 \pm 0.33 \text{ GeV}.$$

For TEVATRON energy $\sqrt{s} = 1800 \text{ GeV}$ our estimation gives $\sigma_{p\bar{p} \rightarrow c\bar{c}+X} \simeq 246 \pm 30 \mu b$; for LHC energy $\sqrt{s} = 14000 \text{ GeV}$, $\sigma_{pp \rightarrow c\bar{c}+X} \simeq 356 \pm 35 \mu b$.

In cosmic ray (CR) physics charmed particles, arising in interaction of primary particle with an atmosphere, are sources of so called "prompt" high-energy muons, carrying away energy from Extensive Air Shower (EAS). A well known problem about the nature of a break ("the knee") in the cosmic rays energy spectrum at $E_{k(Lab)} \approx 3 \times 10^3 \text{ TeV}$ ($\sqrt{s_k} \approx 2.5 \text{ TeV}$) can not be solved without the quantitative information on the contribution of charmed particles in the total muon flux. Obtaining such information is a complex problem which is solved by joint processing the accelerating data (LHC data will be added to them in the coming years) and results which should be received at CR facilities. These are accelerating data on total and inclusive cross sections of hadronic interactions (including cross sections of charm production) and CR data on the flux of muons with energies $E_{\mu(Lab)} \geq 70 \text{ TeV}$.

In conditions of incompleteness of accelerating data, the measurements of "prompt" muons fluxes at energies $E_{\mu} \geq 70 \text{ TeV}$ gain special interest - their results are capable to give the preliminary information about a character of hadronic interactions in the range of ultrahigh energies. For planning and preparation of the experiment, the forecast of expected value of charm production cross section is necessary, provided that laws of this process are extrapolated from accelerating energy region. Our estimation represents one of the variants of such forecast which can be used for calibration of the flux of ultrahigh energy CR muons.

2 Diffraction model of charm production and additive quark model

The offered method of the estimation of charm production cross section is based on the usage of additional set of experimental data. The question is cross sections of proton diffraction dissociation in $p\bar{p}$ - interactions at SPS CERN energies $\sqrt{s} = 200 \text{ GeV}$, 900 GeV [6] and TEVATRON ones $\sqrt{s} = 546 \text{ GeV}$, 1800 GeV [7]. According to these data, the diffraction dissociation cross section depends logarithmically on the energy:

$$\sigma_{DD}(p\bar{p} \rightarrow X) = C_{DD} \ln \frac{s}{s_0}. \quad (2)$$

The basic assumptions consist in the following:

- 1) charm production occurs in process of diffraction dissociation;

2) charm production cross section is extracted from total cross section (2) by quark statistics rules obtained from additive quark model:

$$\sigma_{tot}(p\bar{p} \rightarrow c\bar{c} + X) \simeq k_{c\bar{c}} \times \sigma_{DD}(p\bar{p} \rightarrow X), \quad k_{c\bar{c}} \simeq 0.025 \pm 0.004. \quad (3)$$

These assumptions, from our point of view, have general enough phenomenological character. Formulas (2), (3) have the status of the asymptotic ones. They are fulfilled more precisely, the greater is the energy of interaction. The value of $k_{c\bar{c}} \simeq 0.025$, presented in (3), is obtained from the relationships in Ref. [8]:

$$u\bar{u} : d\bar{d} : s\bar{s} : c\bar{c} = 1 : 1 : 0.38 \pm 0.07 : 0.06 \pm 0.01, \quad (4)$$

here the symbol $q\bar{q}$ designates the number of secondary hadrons containing quark q or antiquark \bar{q} . Existence of similar relationships is predicted by additive quark model (AQM) [9]. Direct check of these relationships is realized in experiments, in which the composition of secondary particles is supervised. A condition of inclusion of charmed particles in quark statistics is an absence of energy restrictions on process of their production. This condition is obviously fulfilled for charmed particles produced in the diffraction region. All numbers appearing in (4), except the one concerning to c -quarks, are obtained by comparison of AQM to the experiment at $\sqrt{s} = 540$ GeV [10]. An estimation of the suppression factor of charmed hadrons $\lambda_c/\lambda_s \approx 0.15$ is based on characteristic assumption for AQM: for $q = s, c, b$

$$\lambda_q \sim \sum_i \frac{2J_i + 1}{M_i^2},$$

where the summation is over all particles and resonances with spins J and masses M , containing a quark q or an antiquark \bar{q} . Each of the statements reflected in formulas (2) - (4) was repeatedly discussed in scientific literature. We shall note, that typical quantitative accuracy of the phenomenological models based on these statements is 10 - 20 %.

First of all we shall find out the opportunities of AQM and logarithmic dependence for cross sections in the description of direct experimental data on charm production in pN and πN interactions at energies $\sqrt{s} = 20 - 40$ GeV. These two hypotheses are reduced to formulas

$$\sigma_{pN \rightarrow c\bar{c}+X}(s) = C_{pN} \ln \frac{s}{s_0}, \quad \sigma_{\pi N \rightarrow c\bar{c}+X}(s) = \frac{2}{3} \sigma_{pN \rightarrow c\bar{c}+X}(3s/2), \quad (5)$$

containing only two free parameters. Numerical values of these parameters are defined by joint fitting of pN and πN data:

$$C_{pN} = 28.84 \pm 2.10 \mu b, \quad \sqrt{s_0} = 18.51 \pm 0.36 \text{ GeV}, \quad \chi^2 = 0.89. \quad (6)$$

Results of fitting are shown in Fig. 1 (πN data are shifted up on $20 \mu b$ for clearness). As it follows from Fig. 1, the phenomenological diffraction model of charm production describes well the direct low-energy data. However extrapolation of these results in the region of high energies $\sqrt{s} = 1000 - 3000$ GeV has no substantiation, certainly.

As it was already marked in the beginning of the Section, there is an opportunity to involve the additional experimental information in the range of SPS - TEVATRON

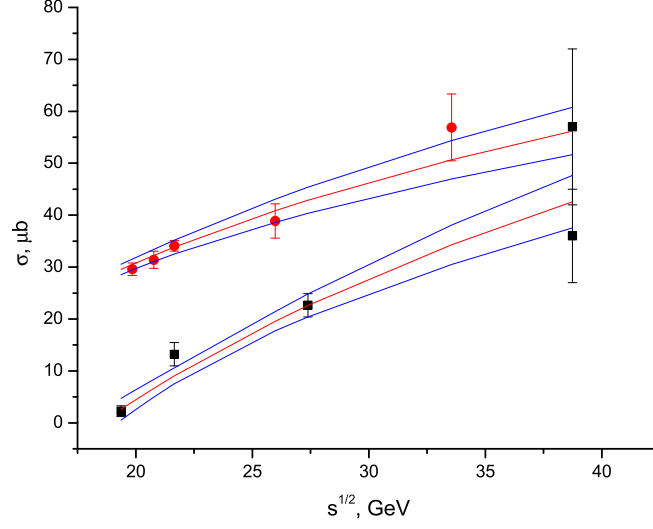


Figure 1: Accelerator data on charm production cross section in pN and πN interactions. πN data are shifted up for clearness.

energies. Cross sections of diffraction dissociation measured at these colliders have the following values:

\sqrt{s} , GeV	200	546	900	1800
σ_{DD} , mb	4.8 ± 0.5	7.89 ± 0.33	7.8 ± 0.5	9.46 ± 0.44

It is easy to verify that the given numbers are fitted in logarithmic dependence. Calculation of values of charm production cross sections from the formula (3), taking into account relationships of AQM (4), gives:

\sqrt{s} , GeV	200	546	900	1800
$\sigma_{p\bar{p} \rightarrow c\bar{c}+X}$, μb	120 ± 21	197 ± 32	195 ± 32	236 ± 38

The obtained values of charm production cross sections have the status of model dependent processing collider data.

In Fig. 2 these results are presented together with the data of direct measurements in the region of low energies. The result of fitting the total data set is:

$$C_{p\bar{p}} = 26.78 \pm 1.44 \mu b, \quad \sqrt{s_0} = 18.23 \pm 0.33 \text{ GeV}, \quad \chi^2 = 0.98. \quad (7)$$

As it is evident from the foregoing, values of the parameters (6) and (7) coincide within the limits of statistical errors. It means the charm production cross section in hadronic interactions is described by universal logarithmic dependence covering both low-energy and high-energy experimental data.

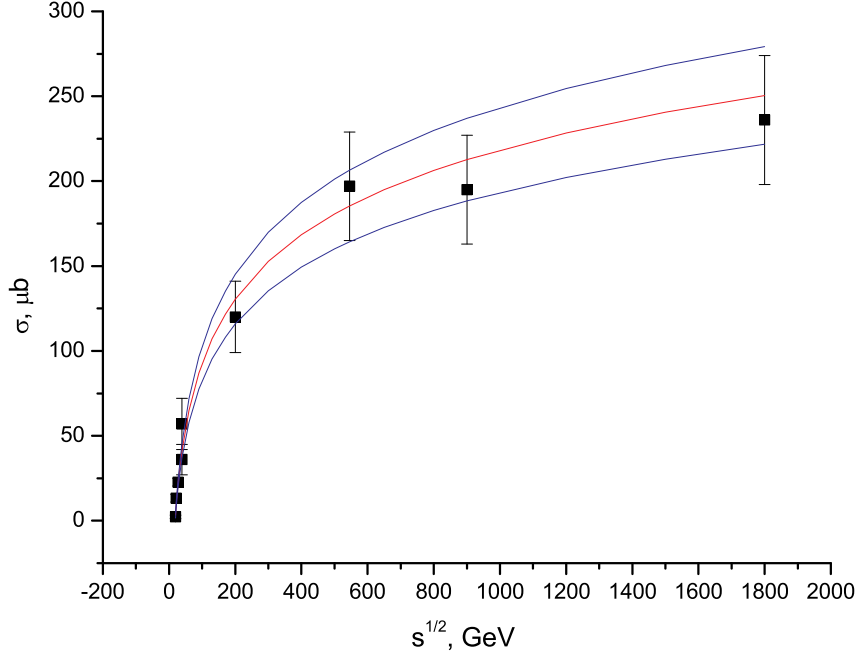


Figure 2: Joint fit of low-energy and high-energy data of charm production.

3 Discussion of results and conclusions

Only the accuracy level is surprising with which low-energy (6) and total (7) parameters of logarithmic function coincide. With regard to ideas of phenomenological models of diffraction production and quark statistics, they were repeatedly tested at processing most various experimental data. These models give reliable quantitative predictions at the accuracy level 10 - 20 % after fixing several parameters by experimental data. Therefore we consider possible to use the results (7) for forecasting cross section of charm production in $pp/p\bar{p}$ interactions in overaccelerating energy range.

In Fig. 3 the dependence of charm production cross section on energy is presented. In Figure is shown the dependence (1) with parameters (7) extrapolated in overaccelerating energy range. The confidence strip of the forecast corresponds to 90 % CL. The expected value of cross section is $\sigma_{pp \rightarrow c\bar{c}+X} \simeq 270 - 300 \mu b$ in the energy region $\sqrt{s} \simeq 3000 - 5000$ GeV and $\sigma_{pp \rightarrow c\bar{c}+X} \simeq 355 \pm 35 \mu b$ at LHC energy $\sqrt{s} = 14000$ GeV.

Using the quark statistics, the total cross section of charm production can be presented as the sum of inclusive cross sections. Appropriate relationships between cross sections [4] are checked experimentally up in the region $\sqrt{s} = 20 - 40$ GeV:

$$\sigma(D_s \bar{D}_s)/\sigma(D^0 \bar{D}^0 + D^+ \bar{D}^-) \simeq 0.2, \quad \sigma(\Lambda_c \bar{\Lambda})/\sigma(D^0 \bar{D}^0 + D^+ \bar{D}^-) \simeq 0.3$$

As it was shown above, a hypothesis of scale invariance of total cross section parameters is experimentally motivated; therefore we expand this hypothesis on the parameters of

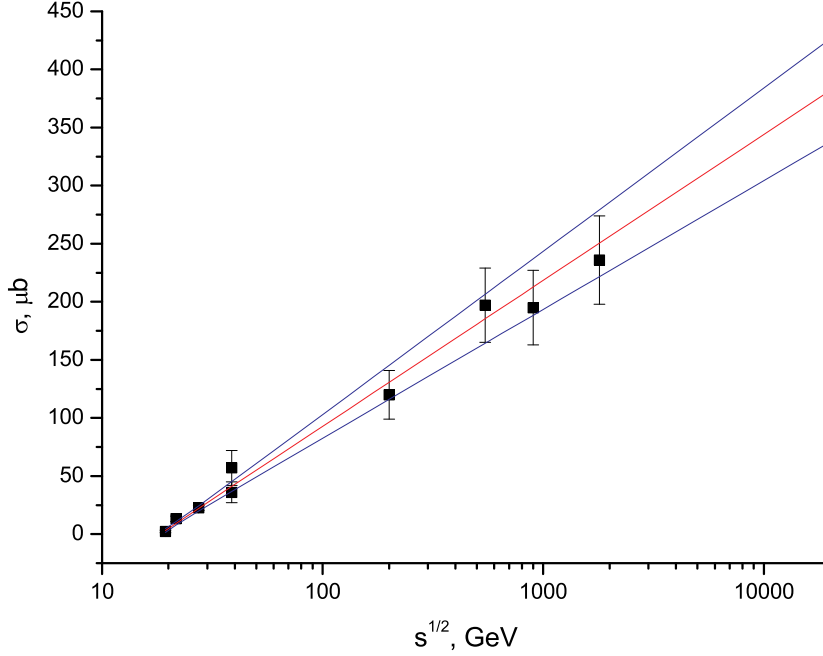


Figure 3: Extrapolation of the charm production accelerator data fit to overaccelerating energy range.

inclusive cross sections. In this case we have in laboratory system

$$\sigma_{D\bar{D}}(E) \approx 154.1 + 17.86 \ln E \text{ } \mu b,$$

$$\sigma_{D_s\bar{D}_s}(E) \approx 30.8 + 3.55 \ln E \text{ } \mu b, \quad (8)$$

$$\sigma_{\Lambda_c\bar{D}}(E) \approx 46.2 + 5.33 \ln E \text{ } \mu b.$$

where E is in PeV ($1 \text{ PeV} = 10^3 \text{ TeV}$). A technique of use of similar type formulas for calculation of an expected flux of "prompt" high-energy muons, accompanying EAS, is described in Ref. [11]. Detection of such muons, in essence, is check of numerical values of factors appearing in formulas (8).

Now the experiment on recording very high energy (VHE) muons ($E_\mu \geq 70 \text{ TeV}$) is carried out at Baksan Underground Scintillation Telescope (BUST) [12]. Preliminary results of this experiment, expected in the near future, will show as far as the offered estimation of charm production cross section is adequate. It should be noted that limiting energy of TEVATRON $\sqrt{s_{max}} = 1.96 \text{ TeV}$ is very close to the energy of the break in CR energy spectrum $\sqrt{s_{knee}} \approx 2.5 \text{ TeV}$. If total cross sections of charm production would be measured at TEVATRON, their small extrapolation would allow to obtain the information necessary for calibration of the flux of VHE muons. In this case, logic and interpretation of the experiment on recording CR muons would get at once a rigid character.

It should be pointed out, there are three possible (and alternative) variants of results, each of which represents the certain interest.

1) The measured flux of CR muons within the limits of measurement errors coincides with calibration flux calculated according to the estimation of charm production cross section (1). In this case the formula (1) can be used for testing microscopic models.

2) The measured flux of CR muons will exceed noticeably the calibration value, but the appropriate cross sections of charm production at energies in the region of a break of CR energy spectrum will stay essentially smaller 10 mb . In this case it will be necessary to recognize, that either quark statistics rules, in that kind in which they were used in the present work, become incorrect in the area of high energies, or the new mechanism of charm production, distinct from the diffraction one, is included at these energies.

3) The measured flux of CR muons will correspond formally to charm production cross section exceeding 10 mb . This result will mean that VHE muons carry away the energy from EAS forming an observable break of CR spectrum (see, for example, [13]). However, it is necessary to note, that sources of such big numbers of VHE muons, most likely, are not reduced to charmed particles - a New physics will required for interpretation of such effect. Certainly for the formulation of new ideas, the data on the flux of CR muons should be considered together with all other accelerating and CR data.

References

- [1] Abe F. et al (CDF Collaboration) 1997 Phys.Rev.Lett.**79**,572.
- [2] Abachi S. et al (D0 Collaboration) 1996 Phys.Lett.B**370**,239.
- [3] D. Acosta et al, Measurement of Prompt Charm Production Cross Section in pp Collisions at $\sqrt{s}=1.96\text{ TeV}$, hep-ex/0307080 v1, 29 July, 2003.
- [4] S.Frixione, M.L.Mangano, P.Nason, G.Ridolfi, CERN-TH/97-16; hep-ph/9702287.
- [5] R.D.St.Denis, J.Phys. G **26** (2000), 541.
- [6] Ansorge et al (CERN-UA-005 Collaboration) Z. Phys **C33**, 175 (1986).
- [7] Abe F. et al (CDF Collaboration) Phys. Rev **D50** (1994) 5535.
- [8] V.G. Grishin, Quarks and hadrons in high energy particle interactions. Energoatomizdat, 1988, p.149.
- [9] V.V. Anisovich, M.N. Kobrinsky, Yu. Niri, Yu.M. Shabelsky, Sov.J. Uspehi fizicheskikh nauk **144** (1984) 553.
- [10] A. Wroblewski, Acta Phys Polonica B16 (1985) 379.
- [11] L.V. Volkova, G.T. Zatsepin, Rus.J. Nuclear Physics **64** (2001) 313.
- [12] V.B. Petkov et al. Proc. of 28 ICRC, Tsukuba, 2003. HE 2.1, p.1207.
- [13] Petrukhnin A. XI Rencontres de Blois "Frontiers of Matter". Blois. France. June 27 - July 3. 1999.